CHARACTERISTICS OF THE X-Y ANTENNA MOUNT FOR DATA ACQUISITION[1]

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Scientific satellite programs demand optimum performance from automatic tracking antenna systems. Certain criteria, such as maximum drive shaft rates and best satellite data transmission conditions, are considered in the design of the antenna mount. In this paper, maximum shaft rates of two-axis mounts are compared under similar satellite pass conditions and the advantages of using an X–Y antenna mount for data acquisition and satellite tracking functions are discussed. Some general design considerations for servo control systems, and a discussion relating the error constants to the satellite rates, are given. A few salient features illustrating the advantages of the X–Y mount from the servo drive system designer's viewpoint are also presented. The paper concludes with a brief description of NASA's 85-foot parabolic X–Y antenna at the Data Acquisition Facility at Gilmore Creek (Fairbanks), Alaska.

INTRODUCTION

Most previous configurations for tracking antennas were developed as parts of radar systems. Since the latter were, for the most part, designed for low-elevation tracking of land vehicles, ships, and distant aircraft, elevation-over-azimuth mounts were developed and have been used almost exclusively for this application.

The first antennas used for satellite tracking and data acquisition employed radar-type elevation-over-azimuth mounts because this was the most common type available commercially. The serious deficiencies of the elevation-over-azimuth mount for satellite tracking immediately became apparent and showed the necessity of using antenna mounts that are optimum for tracking satellites. The development of a new antenna mount configuration was initiated at the Goddard Space Flight Center.

[1] A preliminary version of this paper under the title "The X–Y Antenna Mount for Data Acquisition from Satellites" was published in the *IRE Trans. on Space Electronics and Telemetry*, SET-8(2): 159–163, June 1962.

REQUIREMENTS FOR SATELLITE TRACKING

Satellites are put into orbit to gather scientific data; consequently, the usual prime objective of a satellite tracking antenna is to receive telemetered data from the satellites. Data are generally transmitted by the satellite during most of a pass, and it is desirable that all the data be received; this means that the data acquisition antenna must track the satellite for the maximum length of time. The ideal situation would be to acquire the satellite on the horizon and track it continuously to the other horizon. However, in practice good reception is not possible at very low-elevation angles because of multipath propagation and the higher level of received interference. Antenna sites selected for low interference are usually valleys surrounded by hills, which shield the antenna from man-made interference but prevent data acquisition near the horizon.

Over a period of time, satellites may be observed in all parts of the sky at many of the data acquisition stations. Therefore, a data acquisition antenna must be able to track a satellite at any position in the sky above a few degrees elevation.

The best quality of data reception occurs when the telemetry signal is strongest, i.e., when the satellite is closest to the ground station. The range to a satellite is a minimum when the perigee point of the orbit is directly over the station, that is, in the zenith direction from the ground antenna. Thus, it is most important that a data acquisition antenna be capable of continuous, good tracking through and near the local zenith in order to assure quality reception of the telemetered data.

COORDINATE SYSTEMS

The position of a satellite, as measured from a tracking station, can be described in terms of various systems of coordinates, some of which are illustrated in Figure 1. For example, the position can be described in terms of the direction angles α, β, and γ and the slant range; more commonly, the position is described in terms of the cosines of those angles and the slant range. The position can also be described in terms of the east, north, and vertical components of the slant range; it is anticipated that this system will be used in the future for transmitting predicted positions to various NASA tracking stations. The position is often described in terms of the azimuth angle A, the elevation angle E, and the slant range; but it can also be described in terms of the X angle, the Y angle, and the slant range, as shown in Figure 1.

In the X–Y angle and slant range system adopted by the Goddard Space Flight Center, the X axis is oriented north-south and is parallel to the surface of the earth. The X angle is taken to be zero when the east component of range is zero; limits of ± 90 degrees are set on the value of this angle, and the sign of the angle is taken to be the same as the sign of the east component. The Y angle is taken to be zero when the north component of range is zero; limits of ± 90 degrees are set on the value of the angle, and its sign is taken to be the same as the sign of the north component Thus, for the case illustrated in Figure 1, the X angle has a

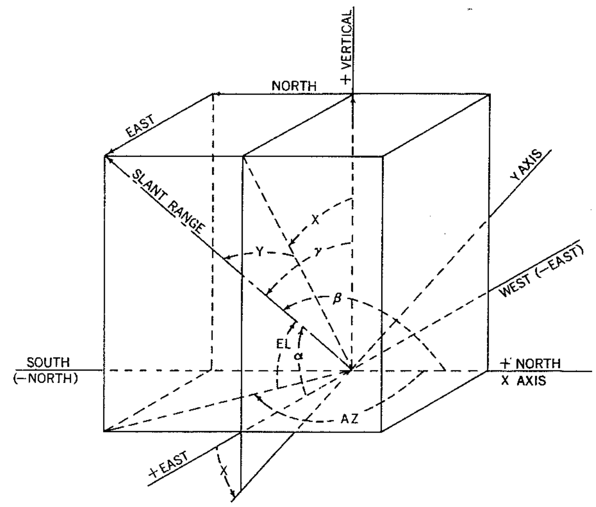

FIGURE 1.—Coordinate systems.

positive value and the Y angle has a negative value.

The familiar arrangement of the primary (azimuth) and secondary (elevation) axes of an elevation-over-azimuth mount is shown in Figure 2. The arrangement of the primary X and secondary Y axes of an X–Y mount[2] is shown in Figure 3.

SATELLITE TRACKING WITH AN ELEVATION-OVER-AZIMUTH MOUNT

To bring certain tracking considerations into sharp focus, let us examine the elevation-over-azimuth mount from the standpoint of its tracking characteristics.

Passes of three orbits, all having the same perigee height and speed, are shown in Figure 4. Let it be assumed that each satellite is at perigee at the time of its closest approach to the station—the time of meridian crossing for the orbits shown. The maximum azimuth shaft speed for each pass, then, is

$$A_{\max}=\frac{\sec E_1}{S_1} V_p, \tag{1}$$

[2] This arrangement of axes has been described as "Cross-Elevation over Elevation" instead of "X–Y" in Cady, W. M., Karelitz, M. B., and Turner, L. A., "Radar Scanners and Radomes," vol. 26 of the Radiation Laboratory Series, New York: McGraw-Hill, 1948, Figure 4.1(c), p. 104.

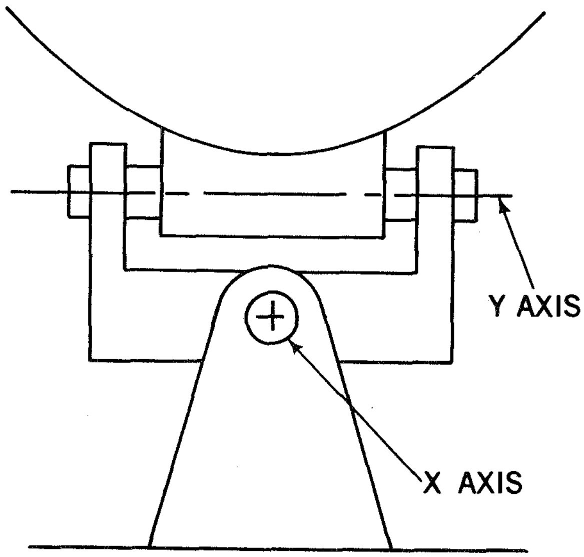

FIGURE 2.—Elevation-over-azimuth mount.

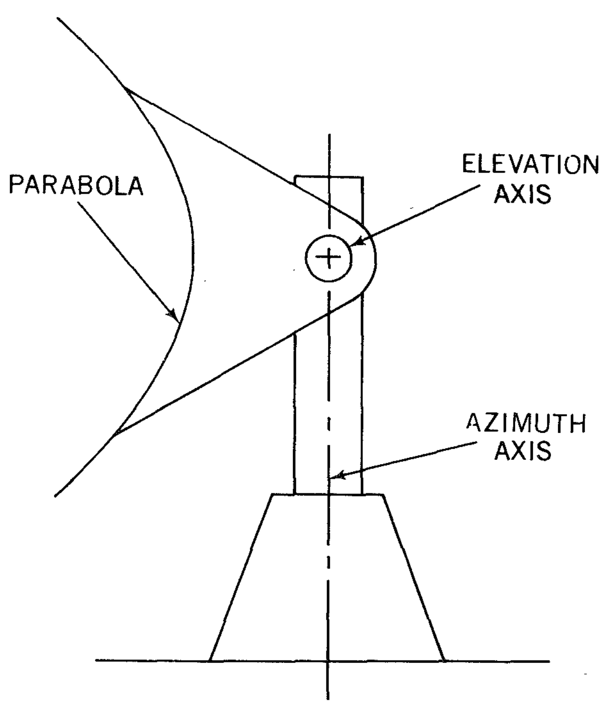

FIGURE 3.—X–Y mount.

where E_1 is the elevation angle at the time of closest approach, S_1 is the slant range at that time, and V_p is the perigee speed of the satellite. For orbit A, crossing the meridian at a low elevation angle, sec E_1 is close to unity and S_1 is large, so the maximum azimuth shaft speed is relatively low. But for orbits B and C, crossing the meridian at successively higher elevation angles, sec E_1 becomes successively larger and S_1 becomes successively smaller. As a result, the maximum azimuth shaft speed increases rapidly as a function of meridian elevation angle, going to infinity at 90 degrees elevation. The azimuth drive, being a physical system, can drive the antenna only at speeds below a certain maximum. Consequently, for any elevation-over-azimuth mount, there is always an area of the sky around zenith in which it is impossible for the mount to follow a satellite because the required azimuth shaft speed exceeds the limiting speed of the drive system. This shortcoming makes the elevation-over-azimuth mount a poor choice for a satellite data acquisition antenna.

THE *X–Y* MOUNT CONCEPT

A "brute force" solution to the problem of tracking through the zenith is to add a third axis[3] to an elevation-over-azimuth mount, but the increased complexity of the servo and drive system for a three-axis mount makes this solution unattractive. It appears more desirable to use a two-axis mount which is better

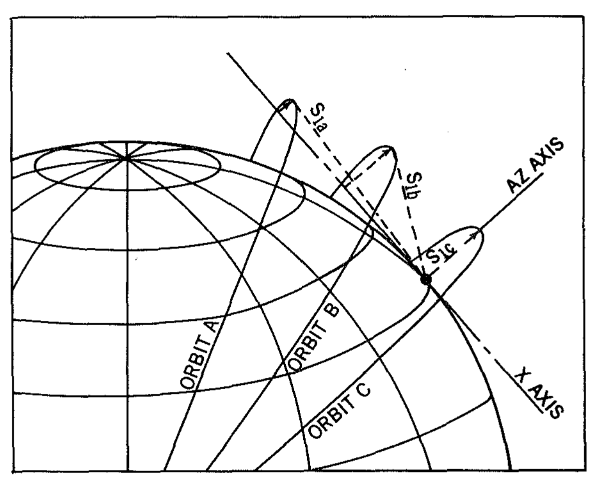

FIGURE 4.—East-west satellite passes with meridian elevation angles of 5°, 30°, and 90°.

[3] Victor, W. K., "Ground Equipment for Satellite Communication," Jet Propulsion Lab. Tech. Report 32–137, August 1, 1961, p. 54.

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suited to satellite tracking, since a two-axis mount with orthogonal axes is the simplest configuration capable of pointing an antenna at any position in the sky.

The gimbal lock, or inability to track at zenith, for an elevation-over-azimuth mount illustrates a characteristic of all two-axis configurations. Any two-axis antenna mount has a gimbal-lock zone in the direction of the primary axis. Satellite tracking requires the absence of gimbal-lock zones above elevation angles of a few degrees. A possible solution is, therefore, to place the gimbal-lock positions on the horizon—in other words, to place the primary axis horizontally, as is done with the *X–Y* mount. Full sky coverage is obtained by orienting the secondary axis orthogonal to the primary axis so that the secondary axis is horizontal when the antenna is pointed at the zenith.

SATELLITE TRACKING WITH AN *X–Y* MOUNT

The worst-case pass with respect to an X axis is a pass on which the satellite, at perigee, crosses the meridian plane in an east-west direction, as illustrated in Figure 4. The maximum X axis speed during such a pass is

$$\dot{X}_{\max}=\frac{\csc E_1}{S_1}V_p. \tag{2}$$

For a pass through the zenith (orbit C) an *X–Y* mount has the lowest possible primary axis speed of any two-axis mount. For east-west passes at successively lower meridian elevation angles, csc E_1 becomes greater, but S_1 also becomes greater and partially cancels the increase in csc E_1; the net result is that $\dot{X}_{\max}$ does not become great until the meridian elevation angle is quite small. But as mentioned previously, it is not possible to get good telemetry reception at low elevation angles; consequently, tracking at these angles is of little interest.

COMPARISON OF TRACKING RATES FOR *AZ–EL* AND *X–Y* MOUNTS

Equation 1 may be rewritten in the form

$$\dot{A}_{\max}=\frac{\csc \gamma_1}{S_1}V_p, \tag{3}$$

where $\gamma_1=90°-E_1$. The angle γ_1 is measured from the primary axis of an *AZ–EL* mount, just as the angle E_1 in Equation 2 is measured from the primary axis of an *X–Y* mount; γ_1 and E_1 can each be described as an "angle off axis." In Figure 5, $\dot{A}_{\max}$ is plotted as a function of γ_1 and $\dot{X}_{\max}$ as a function of E_1, for satellites in circular orbits at various heights above the earth.[4] For a given small angle off axis, it is evident that the maximum azimuth speed is much greater than the maximum X axis speed. In other words, for a given maximum shaft speed capability, an *X–Y* mount can track a satellite at a much smaller angle off the primary axis.

It is shown in Appendix A that the maximum primary-axis acceleration during a worst-case pass is very nearly proportional to the square of the maximum shaft speed. Consequently, for a pass at a given small angle off axis, the maximum azimuth acceleration would be much greater than the maximum X axis acceleration.

The worst-case pass with respect to a secondary axis (either elevation or Y) is one on which the satellite travels through the zenith in a direction normal to a vertical plane containing the secondary axis. If we ignore the rotation of the earth, the shaft rates of the secondary axis during such a pass would be identical to the shaft rates of the X axis during orbit C of Figure 4; the maximum speed of the secondary axis would be equal to $\dot{X}_{\max}$ at $E_1=90$ degrees, as plotted in Figure 5.

SERVO SYSTEM CONSIDERATIONS

Servo Control System

In the design of the servo control system, consideration should be given to such factors as: system response and stability, dynamic

[4] The shaft speeds in Figure 5 were calculated for a non-rotating spherical earth of radius equal to the actual equatorial radius. More exact calculations for a particular station would take into account (1) the increase in slant range due to flattening of the earth at the latitude of the station, (2) the surface speed of the earth at that latitude, and (3) the direction of the orbit (direct or retrograde). At 60 degrees latitude, these factors could affect the shaft speeds for a 100-nautical-mile satellite by as much as 12 percent.

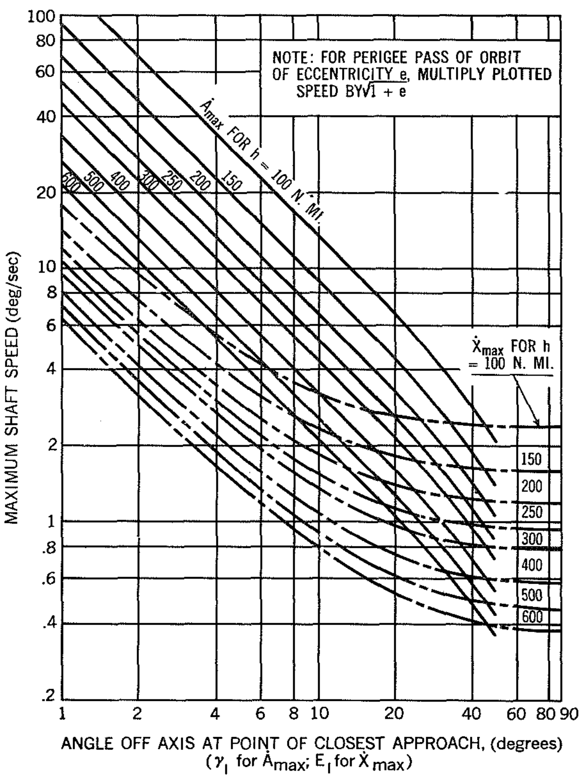

FIGURE 5.—Maximum shaft speeds on worst-case passes of circular orbits.

behavior at no-load and full-load conditions, and oscillation due to random load disturbances applied to the output shaft. Other factors which influence the design approach are large steady-state wind-induced torques and transient wind gusts. Within the framework of these factors, it is not possible to employ a standard or fixed method of synthesizing the optimum control system design, particularly since no previous knowledge of the *X–Y* system is available. Hence an intuitive, heuristic approach was pursued in the design of the servo control system for the first *X–Y* mount. Design parameters such as the velocity constant K_v and/or the acceleration constant K_a control the manner in which the system design is carried out. The constants K_v and K_a can be specified in terms of tracking servo bandwidth and maximum tracking rates. If, in the region of interest, the same tracking accuracy is specified for an *X–Y* system as for an equivalent *AZ–EL* system, the lower *X* shaft rate requirements for near-zenith tracking allow lower error coefficients values to be selected for the *X–Y* system; hence, the design limits on the system can be relaxed. The mathematical relationship equating the *X* axis lag error to the time derivatives of the input variable, satellite motion, can be expressed as follows:

$$e_x(t)=\frac{\dot{x}}{K_v}+\frac{\ddot{x}}{K_a}+\cdot\cdot\cdot\cdot\cdot\cdot$$

The actuating signal $e_x(t)$ is the lag error in the control system loop and X is the input variable, that is, the description of the satellite's motion. From the above equation, it can be inferred that if the error coefficients are not changed, lower shaft rates decrease the lag in the system.

Servo Drive System

Because the total power required to move the antenna is a function of its maximum acceleration and velocity, it is of primary importance not only to select a power element with an adequate power rating, but also to choose an antenna configuration that requires lower shaft rates. On the basis of the foregoing discussion, *X–Y* mounts seem to possess the characteristics which lend themselves most appropriately to the specified conditions.

Such factors as antenna inertia, friction load, unbalanced mass load, and wind load, as well as the maximum velocity and acceleration, control the selection of the drive element. Consequently, the lower shaft rates allow the choice of a drive element with a lower power rating. The last assumption is based on the premise that the duty cycle—the factor which establishes the heat dissipation property of the drive element—is not affected by other considerations.

It was mentioned earlier that the singularity or the gimbal-lock condition in the *X–Y* case exists about the *X* axis. This singularity is best described as a "keyhole" interference contour about the *X* axis on the horizon. In the data acquisition function, one of the operational conditions is the demand for maximum sky coverage where the best tracking conditions exist; in the region of interest, the *X–Y* mount provides maximum usable sky coverage at lower shaft rates.

DISCUSSION

The elevation-over-azimuth mount cannot continuously track satellites which reach high elevation angles; since it is here that the telemetry data are of the highest quality, this type of mount is therefore undesirable for satellite data acquisition antennas.

On the other hand, the tracking characteristics of an X–Y mount meet the requirements for satellite tracking. The zone of minimum primary-axis speed matches the zone of best-quality data transmission. Zones of excessive shaft speed occur near the horizon around the ends of the X axis, but the data quality in these zones is poor, and the desirable sites for data acquisition antennas are those with natural horizon shielding from man-made interference. The X–Y mount will track satellites through nearly the entire sky with moderate shaft speeds and accelerations. Thus, efficient tracking can be accomplished with moderate drive and servo systems.

The X–Y mount has another advantage. It is not necessary to use slip rings, rotary RF joints, or extensive cable-wrap systems to bring out the RF and power lines. Each axis travels only ± 90 degrees; thus, a simple, flexible section of cable is all that is needed to go across either axis. With the requirement for high receiver sensitivity for satellite data acquisition, this becomes a worthwhile advantage by eliminating a source of possible RF interference.

The Goddard Space Flight Center has sponsored the development of two types of X–Y antenna mounts for data acquisition from satellites; one of these was for an 85-foot-diameter parabolic antenna. This antenna (Fig. 6) was constructed to GSFC specifications by the Blaw-Knox Co. at a site in the Gilmore Creek Valley 12 miles north of Fairbanks, Alaska. The site is located in a small valley and the surrounding hills provide RF shielding from outside sources. The Gilmore Creek Valley has a horizon 9 degrees in the north and 8 degrees in the south; and the horizon decreases to about 2½ degrees in the west and 5 degrees in the east. The antenna is a paraboloid of revolution with a focal length of 36 feet. Its surface consists of doubly curved aluminum

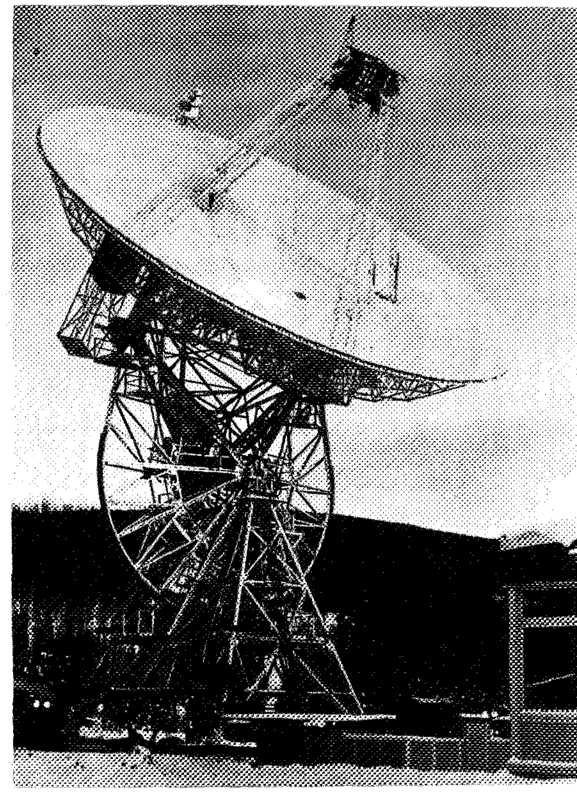

FIGURE 6.—X–Y mounted 85-foot antenna at the NASA data acquisition facility, Fairbanks, Alaska.

sheet panels. The X–Y mount was designed to provide optimum satellite tracking without requiring excessive shaft velocities from the antenna drive system. The antenna is capable of tracking at shaft speeds from 0 to 3 deg/sec with shaft accelerations of up to 3 deg/sec^2; this is sufficient for acquisition and tracking of 150-nautical-mile satellites throughout the sky above the local horizon. The antenna has six operational modes; it will automatically track on a satellite signal, it can be driven by a teletype tape input, it can be manually directed, it can be slaved to another antenna, or it can be operated in either of two search modes for initial acquisition.

ACKNOWLEDGMENTS

The authors wish to acknowledge the many contributions of Mr. C. H. Looney, Jr., Mr. P. A. Lantz, and Mr. V. R. Simas to the development of the X–Y mount.

Appendix A

APPROXIMATE EXPRESSIONS FOR SHAFT SPEED AND ACCELERATION

Figure A–1 depicts an approximation to a satellite's motion relative to a tracking station. An azimuth axis and an X axis (on separate antennas) are located at the station. At time t_1 the satellite lies in the meridian plane (the plane of the front view) and is traveling directly eastward at a velocity V.

Let it be assumed that the earth does not rotate. Also, let it be assumed that the satellite continues to travel directly eastward at the constant velocity V; in other words, let it be assumed that the north and vertical components of slant range, as measured from the station, are constant during the pass.

At time t_1 the azimuth axis speed is at its maximum value for the pass, namely,

$$\dot{A}_{\max}=\frac{V}{S_1 \sin \gamma_1}. \qquad \text{(A–1)}$$

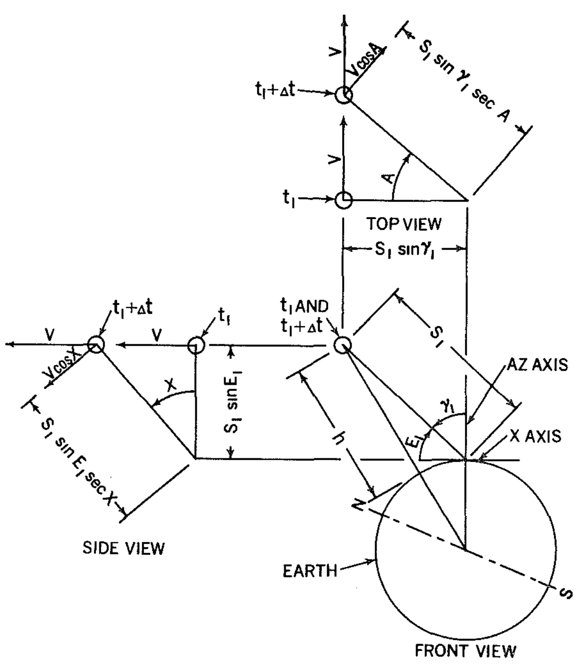

FIGURE A1.—Approximation to motion of a satellite.

At time $t_1+\Delta t$, the satellite reaches a point defined by the angle A in the top view. This azimuth shaft angle is

$$A=\tan^{-1}\frac{V\Delta t}{S_1 \sin \gamma_1}=\tan^{-1}[(\dot{A}_{max})\Delta t]. \qquad \text{(A–2)}$$

At this time, the azimuth speed is

$$\dot{A}=\frac{V \cos A}{S_1 \sin \gamma_1 \sec A}=\dot{A}_{\max} \cos^2 A \qquad \text{(A–3)}$$

and the azimuth acceleration is

$$\ddot{A}=-2(\dot{A}_{\max})^2 \cos^3 A \sin A. \qquad \text{(A–4)}$$

By setting the derivative of $\ddot{A}$ with respect to A equal to zero, it is found that the absolute value of $\ddot{A}$ reaches a maximum at $A=\pm 30$ degrees, and hence.

$$|\ddot{A}|_{\max}=\frac{3\sqrt{3}}{8}(\dot{A}_{\max})^2 \text{ rad/sec}^2,$$

where $\dot{A}_{max}$ is expressed in rad/sec. In more convenient units,

$$|\ddot{A}|_{\max}=\frac{\pi\sqrt{3}}{480}(\dot{A}_{\max})^2 \text{ deg/sec}^2, \qquad \text{(A–5)}$$

where $\dot{A}_{\max}$ is expressed in deg/sec.

In a similar fashion, it can be shown that

$$\dot{X}_{\max}=\frac{V}{S_1 \sin E_1}, \qquad \text{(A=6)}$$

$$X=\tan^{-1}[(\dot{X}_{\max})\Delta t], \qquad \text{(A–7)}$$

$$\dot{X}=\dot{X}_{\max} \cos^2 \dot{X}, \qquad \text{(A–8)}$$

$$\ddot{X}=-2(\dot{X}_{\max})^2 \cos^3 X \sin X \qquad \text{(A–9)}$$

where $\dot{X}_{\max}$ is expressed in rad/sec, and

$$|\ddot{X}|_{\max}=\frac{\pi\sqrt{3}}{480}(\dot{X}_{\max})^2 \text{ deg/sec}^2, \qquad \text{(A–10)}$$

where $\dot{X}_{\max}$ is expressed in deg/sec.

Values of maximum shaft accelerations calculated from Equations A–5 and A–10 have been compared with values of maximum acceleration calculated in Goddard Space Flight Center's IBM 7090 orbital prediction programs, for certain passes of circular orbits at heights of 100 and 600 nautical miles. The passes were all "worst-case" in the sense that the satellite velocity was, in each instance, normal to the meridian plane at the time of meridian crossing.

For passes at $\gamma_1=10$ degrees, the approximate value of $\ddot{A}_{max}$ exceeded the IBM 7090 value by less than 0.5 percent, for both orbits. For passes at $E_1=10$ degrees, the approximate value of $\ddot{X}_{max}$ exceeded the IBM 7090 values by 2.3 percent for the 100-mile orbit and by 7 percent for the 600-mile orbit. At equal angles off axis, the approximation is better for $\ddot{A}$ than for $\ddot{X}$ because the time interval between the instant of maximum speed and the instant of maximum acceleration (at a shaft position approximately 30 degrees away) is smaller for the azimuth axis case than for the X axis case. As this time interval becomes smaller, the satellite moves a shorter distance along its curved orbital path and the earth rotates through a smaller angle about its spin axis; hence, the actual motion of the satellite during the interval more nearly approaches the type of motion depicted in Figure A1. Consequently, the approximations for shaft acceleration are relatively good for passes at small angles off axis, for low perigee heights, and for high perigee velocities.

For meridian crossings at large angles off axis, it was found that the approximations were not terribly bad, especially for low perigee heights. At $\gamma_1=85$ degrees, the approximate value of $\ddot{A}_{max}$ was about 1 percent greater than the IBM 7090 value for the 100-mile circular orbit, and about 8 percent greater for the 600-mile circular orbit. At $E_1=85$ degrees, the approximate value of $\ddot{X}_{max}$ was about 3.5 percent greater than the IBM 7090 value for the 100-mile circular orbit, and about 17.5 percent greater for the 600-mile circular orbit. At $E_1=88$ degrees, the approximate value for $\ddot{X}_{max}$ for a perigee pass of the highly elliptical EGO orbit, at a height of 150 nautical miles, exceeded the IBM 7090 value by only 2.3 percent.

For all of the passes calculated on the IBM 7090, with meridian crossings at both small and large angles off axis, the maximum shaft accelerations occurred at shaft angles very close to ± 30 degrees.

It is believed that the foregoing approximate expressions for shaft speed and acceleration are sufficiently accurate for purposes of designing servo control and drive systems for most tracking and data acquisition antennas.